The shift team formation problem in multi-shift manufacturing operations

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THE SHIFT TEAM FORMATION PROBLEM IN MULTI-SHIFT MANUFACTURING OPERATIONS

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SOM-theme A: Primary processes within firms

Abstract
This paper addresses the problem of assigning operators to teams that work in single-, two-, or three-day shift systems. The problem was motivated by, and illustrated with a case situation encountered in Dutch manufacturing industry. The problem addressed forms an extension of cell formation problems which are currently in the phase of addressing labor-related issues in cell design. A generalized goal problem formulation is presented to address multiple, conflicting objectives covering cross-training of workers, ensuring adequate levels of labor flexibility and minimizing labor-related costs. The proposed solution procedure consists of two phases. In the first phase, shift systems, in which applicable machines and the sizes of each shift team are identified. The next phase deals with assignment of operators to various teams and identification of specific cross-training needs for various workers. This phase involves the use of interactive goal programming. The methodology is illustrated by details from the case situation as well as a numerical example.

Keywords: manufacturing, shift systems, goal programming

1. Introduction

Shift work is common in manufacturing operations, although it is known to have many negative effects on workers' motivation, sleep, health and social problems (e.g., Moore-Ede 1993). Shift work is necessary in many manufacturing firms to augment productive capacity and to ensure efficient use of expensive equipment.

Shift work can vary considerably in its specific characteristics. Continuous shift systems require weekend working whereas discontinuous systems occur in organizations that operate Monday through Friday. Shift work varies with respect to start and stop times of workers, length of the shifts, length of time off between shifts, and the order of shift rotation. Shift work can be permanent where each employee works only one type of shift. In rotating shifts, workers rotate their hours to include each type of shift (Daus et al. 1998). In practice, more than one shift work system may be used in a manufacturing department. Some machines and workers may, for instance, be active in a twice-daily shift system, while other machines and workers are organized in a thrice-daily shift system.

Shift work requires a skillful division of labor into teams, and choices relating to which workers will work during the same time periods. This paper addresses the problem of assigning operators to various teams that may be present in a multi-shift work system. Shifts also result in labor resources being spread thin at times, which requires a carefully devised cross-training program. Accordingly, cross-training needs of workers are also considered in this paper. This assignment problem is typically faced as a medium-term planning problem, to be solved a few times a year.

The problem dealt with in this paper was motivated by a case situation (a Dutch manufacturing firm) employing manufacturing cells. It is naturally applicable for traditional job shops, but can also be seen as falling within the realm of a relatively new stream of research work in cellular manufacturing. When a firm converts from a functional layout to cellular manufacturing, two major sets of resource reallocations (and relocations) take place. First, functionally specialized (and functionally located) machine pools are partitioned and individual machines relocated to cells. Second, functionally-specialized labor pools are also partitioned, and individual workers reassigned to cells. When such labor pools are partitioned, cross-training is required within the cells to provide adequate flexibility. Many labor-related issues, such as avoiding load imbalances, ensuring adequate levels of cross-training, minimizing hiring of new workers, minimizing inter-cell movements of workers, etc., are important considerations that need to be addressed in cell formation. Cell formation methods, with a few exceptions (Min and Shin 1993, Süer 1996, Askin and Huang 2001, and Suresh and Slomp 2001), have generally not considered the important, labor-related aspects.

Most cell formation methods implicitly assume that the allocation and training of workers is a minor problem and can be solved easily in practice. In the case of expensive and complex machinery, however, this may not be the case. Most cell formation methods are more devoted to grouping of parts and machines into cells, without considering labor-related issues.

Studies that have addressed labor issues include the work of Min and Shin (1993), who presented a mixed-integer goal programming (GP) formulation for simultaneously forming machine and human cells. This formulation cannot be solved efficiently and, therefore, a sequential heuristic in which two smaller GP problems have to be solved sequentially was proposed. The first GP problem concentrates on the assignment of parts and machines to cells. The second GP problem focuses on the assignment of workers to the various cells. A basic assumption in the problem formulation of Min and Shin (1993) is that operators are linked with the various parts by means of so-called 'skill matching factors'. A skill matching factor indicates to what extent a worker is able to produce a part. These factors are used for the optimization of the operator assignment problem. Cross-training issues were not considered in this work.

Süer (1996) presented a two-phase hierarchical methodology for operator assignment and cell loading in labor-intensive manufacturing cells. Here the major concern is the determination of the number of workers in each cell and the assignment of workers to specific operations in such a way that worker productivity is maximal.

A functional arrangement of tasks was assumed in each cell, without considering training and multi-functionality problems.

Askin and Huang (2001) focused on the relocation of workers into cells and the training needed for effective cellular manufacturing. They proposed a mixed integer, goal-programming model for guiding the worker assignment and training process. The model integrates psychological, organizational, and technical factors. They presented greedy heuristics to solve the problem. Askin and Huang (2001) assumed that the required skills are cell dependent and that workers may need some additional training, again without considering cross-training issues.

Suresh and Slomp (2001) proposed an interactive, multi-objective methodology for design of cells, which includes labor-grouping considerations. The method synthesizes the capabilities of new pattern recognition methods for rapid clustering of large routings data sets, with multi-objective optimization capabilities of mathematical programming. After part-machine grouping, considering capacities and volumes, the method addresses labor grouping issues, especially partitioning of functionally-specialized labor pools, and factors such as minimization of hiring and cross-training costs, ensuring balanced loads for workers, minimization of inter-cell movements of workers, and providing adequate levels of labor flexibility.

The works of Min and Shin (1993), Süer (1996), Askin and Huang (2001) and Suresh and Slomp (2001) do not consider the issue that operators in manufacturing cells may work in different shifts. This paper may thus also be seen as extension of this research stream in considering labor–related issues further.

When considering machine and labor constrained systems, a body of literature pertaining to *dual resource-constrained (DRC) systems,* i.e. machine-and-labor situations (e.g., Treleven 1989; Malhotra, *et al*. 1993), is of particular relevance. Many results from DRC system investigations and other studies (e.g., Ebeling and Lee 1994) can be utilized in the context of ensuring adequate levels of cross-training and labor-related flexibility, as we see later in the paper.

Certain aspects of the assignment problem dealt with in this paper are similar to those of the shift scheduling problem introduced by Edie (1954) which involves determining the number of employees to be assigned to each shift and specifying the timing of their relief and lunch breaks. The most common objective in the shift scheduling literature is to minimize staffing costs. The typically used approach of set-covering formulations supports the design of a mathematical model for the assignment problem in this paper. Cross-training issues are rarely dealt with in shift scheduling literature. An exception in literature that includes cross-training issues is the work of Brusco and Johns (1998). They studied the effect of cross-training policies in a staffing problem for maintenance staff employees at a paper mill and presented a preemptive goal-programming model to solve the problem. The situation presented by Brusco and Johns (1998), however, does not consider dual resource elements such as the connection between machine and required qualification level.

The purpose of this paper is threefold. First, the paper presents a problem that is not dealt with in past literature, as far as the authors are aware. As indicated before, the problem addressed also falls within the cell formation problem of cellular manufacturing. The problem was motivated by a case situation encountered in Dutch Industry, which also serves to illustrate the practical context of the problem. Second, the paper presents a general mixed integer goal programming formulation of the problem, which indicates the interrelatedness of the production planning and the operator assignment problem. Third, the paper presents a two-phase heuristic methodology, which decomposes the production planning and operator assignment problem. The applicability of the proposed methodology is illustrated by using information of the case situation mentioned above. The problem has been formulated to be of generalizable value for labor assignment problems in multi-shift manufacturing operations.

This paper is organized as follows. Section 2 describes the problem context and the motivation of this paper driven by the case situation. Section 3 presents a generalized mixed integer goal programming formulation. A pragmatic solution procedure and a numerical example, in which data from the case situation is applied, are described in sections 4 and 5, respectively. These are followed by the conclusions in Section 6.

2. Problem Context and Motivation

The problem addressed in this paper was motivated by the problems faced by a firm that produces by means of manufacturing cells. Besides highlighting the general elements of this problem, it also serves to highlight certain elements of concern while converting to CM. It serves as an empirical driver to the mathematical formulations presented below, in sections 3 and 4.

This firm manufactures parts and small subassemblies used in electro-mechanical industry. Important manufacturing processes include machining/turning operations, sheet-metal processing, strip and tool bound punching, electrostatic painting, galvanic plating, and construction and assembly. About 140 employees are directly involved in the manufacturing process. Until 1993, the manufacturing department was organized in 14 relatively autonomous manufacturing cells. Cellular manufacturing was implemented in 1987.

Since 1993, several changes were made to the cellular system of the firm. Basically, the firm moved from a cellular manufacturing system to a system with more functionally-organized cells (Molleman *et al*. 2002). Within this context, the five cells responsible for mainly machining and turning operations were reorganized into two cells (I and II). An important consideration of moving to more functionally-organized cells was the decision not to divide some important machine types among more than one cell. Furthermore, larger cells offer the economy of scale necessary for justifying new technology. The layout within each of the cells was designed in co-operation with the workers. The two cells were implemented satisfactorily in 1995. Figure 1 presents the current layout of the machining and turning department.

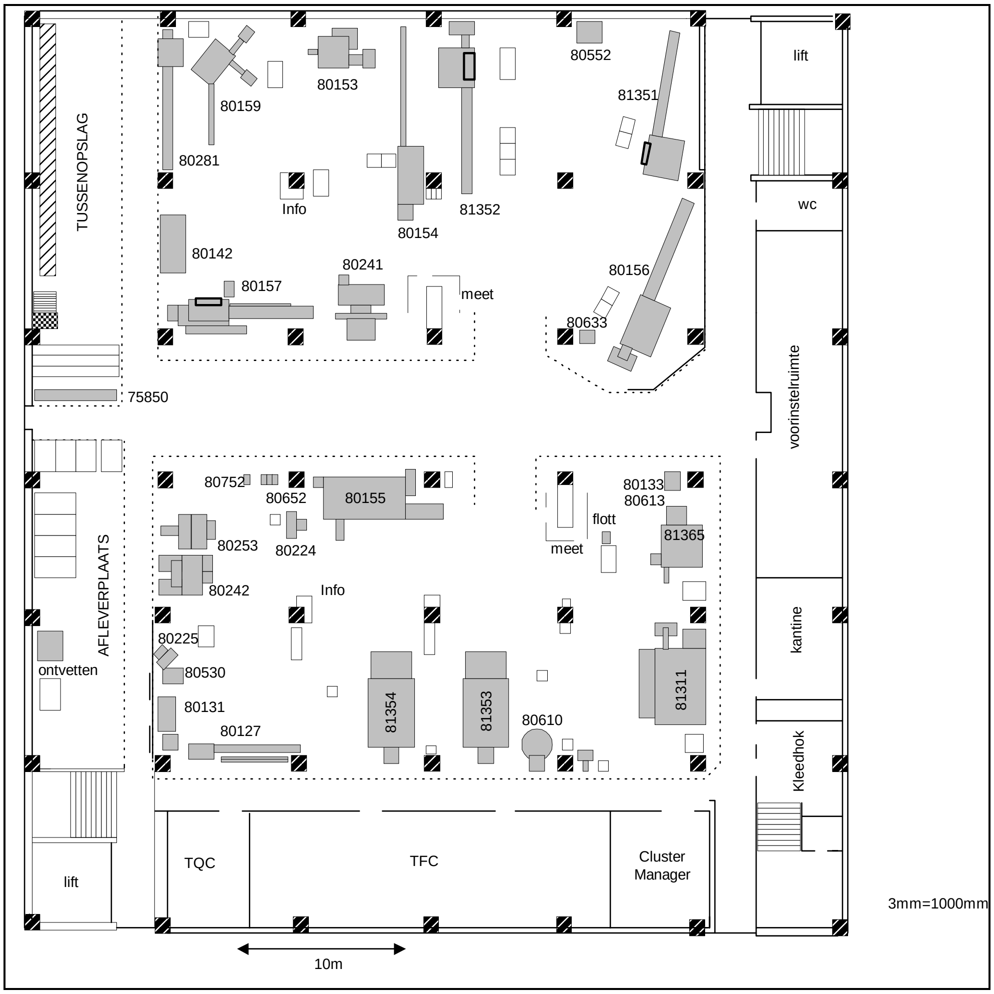

Figure 1. The layout of the machining and turning department

The two cells are to a large extent independent. Cell I is responsible for rotation symmetric part types, while cell II manufactures the prismatic part types. There are few inter-cell relations. The characteristics of the part types produced in both cells are provided in Table 1.

TABLE 1 Characteristics of the part types to be produced in the two cells

	Cell I	Cell II
Total number of different part types for which the cell has been responsible	9500	4500
Number of production orders per period (4 weeks)	140	70
Number of operations per part type which are performed in the cell	1.3 (range 1-3)	1.6 (range 1-4)
Batch sizes	250 (range 30-1500)	100 (range 10-1000)
Hours required per production order in the cell	12.9 (range 1-20)	29.9 (range 1-40)

The sizes of the two cells vary somewhat. Cell I consists of 13 major machines that have to be operated by 18 workers. Cell II includes 9 major machines and 11 workers. Some workers are able to perform on (some) machines in both cells. The salary levels of the workers are dependent on their skills and the shift systems in which they work. Each machine requires a certain skill level. The basic salary of a worker depends on the highest skill level required for this worker. Workers are more or less multifunctional. Each step in the skill-related salary system (C-D-E-F-G) corresponds with a salary increase of approximately 90 Euros (€) per month. Additional salary costs are related to the shift systems in which the workers participate. The firm basically applies three shift systems simultaneously: a 1-daily-shift system, a 2-daily-shift system, and a 3-daily-shift system, five days per week. The 2-daily-shift system leads to a 13.3% salary increase (about € 180 per month, depending on the current salary of the employee), the three-shifts system to an 18.8 % increase. Table 2 presents the labor-machine information that is used by the production manager to control his workforce. Next to the hours required by each machine, some time also is needed for additional tasks, such as quality control, shop floor control and material transport. This latter information is not included in the table.

By means of trend analysis and MRP-data, the production manager rather precisely knows the annual demand on machine level. This demand is not completely stable over the year; there is a small seasonal pattern. The basic philosophy of the production manager is to have relatively small fixed staff for which there is always work. In case of an increase in demand, which happens seasonally, work will be subcontracted to other firms. The mix of work will fluctuate during the year. This, along with the presence of absenteeism, impels the necessity of multi-functional labor.

TABLE 2. Labor-machine information

machine skill level			D	D	D	E	D	E	E	F
machine training time (wks)			40	52	52	80	40	40	40	120
annual hours required			1661	2896	738	1719	1401	510	1755	2738
efficiency factor			1	1,8	3,5	1	1	1,8	1	1
machine in cell			I	I	I	I	I	I	I	I
worker	**cell**	**current salary level (based on reqd. skills)**	**80253 Milling**	**80127 Aut.turn.**	**80133 Aut.turn.**	**80155 CNC turn.**	**80205 Milling**	**80225 Milling**	**80242 milling**	**81353 CNC cent.**
1	I	D		1	1					
2	I	E	1		1				1	
3	I	E	1		1				1	
4	I	F	1						1	
5	I	F	1						1	
6	I	G	1			1	1		1	1
7	I	G	1				1		1	1
8	I	F	1				1		1	1
9	I	F	1				1		1	1
10	I	F	1						1	
11	I	F	1				1		1	1
12	I	F	1						1	1
13	I	D		1				1		
14	I	E	1						1	
15	I	D				1			1	
16	I	C					1			
17	I	E	1						1	
18	I	D								
19	II	F	1		1				1	
20	II	F	1					1	1	
21	II	F	1		1				1	
22	II	F								
23	II	F								
24	II	E								
25	II	E				1				
26	II	E								
27	II	E								
28	II	E								
29	II	E			1					

TABLE 2. Labor-machine information (continued)

machine skill level			F	F	F	D	F	D	E	E
machine training time (wks)			120	120	120	40	80	52	80	80
annual hours required			2114	3377	1992	1126	0	1212	3258	2127
efficiency factor			1	1,1	1	1	1	1	1,2	1
machine in cell			I	I	I	I	I	II	II	II
worker	**cell**	**current salary level (based on reqd. skills)**	**81354 CNC cent.**	**81365 CNC cent.**	**81311 CNC cent.**	**80610 CNC dril.**	**80228 hole mill.**	**80142 Cent.turn.**	**81351 CNC turn.**	**80153 CNC turn.**
1	I	D						1		
2	I	E		1				1		
3	I	E		1						
4	I	F			1					
5	I	F			1					
6	I	G	1			1		1		
7	I	G	1			1		1		
8	I	F	1			1		1		
9	I	F	1			1		1		
10	I	F			1			1	1	1
11	I	F	1				1			
12	I	F	1			1		1		
13	I	D								
14	I	E						1		
15	I	D				1				1
16	I	C								
17	I	E								
18	I	D								
19	II	F						1	1	
20	II	F						1	1	
21	II	F						1	1	
22	II	F			1			1		
23	II	F						1	1	
24	II	E				1			1	
25	II	E			1			1	1	
26	II	E						1		1
27	II	E						1		1
28	II	E						1		1
29	II	E		1				1	1	

TABLE 2. Labor-machine information (continued)

machine skill level			E	E	E	F	D	F
machine training time (wks)			80	80	80	80	40	80
annual hours required			3323	2343	4402	4233	491	2397
efficiency factor			1,1	1,2	1,5	1,5	1	1,2
machine in cell			II	II	II	II	II	II
worker	**cell**	**current salary level (based on reqd. skills)**	**80159 CNC turn.**	**80154 CNC turn.**	**81352 CNC turn.**	**80156 CNC turn.**	**80241 Milling**	**80157 index**
1	I	D						
2	I	E					1	
3	I	E					1	
4	I	F					1	
5	I	F					1	
6	I	G					1	
7	I	G		1			1	
8	I	F					1	
9	I	F		1			1	
10	I	F	1			1	1	
11	I	F					1	
12	I	F					1	
13	I	D						
14	I	E					1	
15	I	D	1					
16	I	C						
17	I	E					1	
18	I	D						
19	II	F					1	
20	II	F		1	1	1	1	
21	II	F		1	1	1	1	
22	II	F			1	1		
23	II	F			1	1		
24	II	E						
25	II	E		1				1
26	II	E	1	1				1
27	II	E	1					
28	II	E	1					
29	II	E						

TABLE 3 Teams in a multi-shift situation

Shift\Week	1	2	3	4	5	6
morning	A B_1 C_1	A B_2 C_3	A B_1 C_2	A B_2 C_1	A B_1 C_3	A B_2 C_2
afternoon	B_2 C_2	B_1 C_1	B_2 C_3	B_1 C_2	B_2 C_1	B_1 C_3
night	C_3	C_2	C_1	C_3	C_2	C_1

Depending on the mix of work, all three shifts systems may be in operation. Intriguing questions concern the issue of which, and how many workers should be allocated to each shift work system, and which workers have to work together in a team. A team is defined here as a group of workers who work in the same shift system and at the same time. Another question concerns cross-training. It may be needed that one or more workers need some additional cross- training in order to gain a stable work situation.

Table 3 shows that, on the basis of three different shift work systems, six teams need to be created. Team A works in a 1-daily-shift system, teams B1 and B2 perform their work in a 2-daily-shift system, and teams C1, C2 and C3 work in 3-daily-shift system. All the teams work five days per week. Table 3 presents a phase-delay schedule for the 3-daily-shift system, which means that, should there be a shift change, workers change shifts in forward direction, from morning shift to afternoon shift, from afternoon shift to night shift, or from night shift to morning shift. Phase-delay schedules appear to be superior to phase-advance schedules (Barton and Folkard 1993). Table 3 indicates the presence of a repetitive team-scheduling pattern with a cycle time of six weeks. After six weeks, the team scheduling starts in the same setting. The cycle time will be different in case of other organizational arrangements. Hung (1997) presented algorithms for shift work scheduling for two work-week scenarios. The cycle times are different for each scenario. The work schedule presented in Table 3 has to be seen as a particular example.

The problem addressed is a general problem faced by factory managers. In every manufacturing cell or department, *given a set of machines, a set of workers with various functional capabilities and levels of skill, and given a set of customer* *demand, what is the best assignment of workers to teams, and what additional training is needed?*

This problem can be seen as a tactical, medium-term planning problem that has to be solved a few times a year. It is clearly a standard problem faced by shop floor managers; yet, the authors have found that the problem has been insufficiently addressed in the literature.

3. A General Problem Formulation (Problem P1)

Given the presence of multiple, conflicting goals, and a combinatorial problem setting, the problem can be naturally stated as a general mixed-integer goal programming formulation. Accordingly, in this section we present a goal program that attempts to "satisfice" among the conflicting goals of:

(i) Minimizing additional salary costs of assigning workers to 2-shift and 3-shift systems;

(ii) Minimizing additional salary costs of elevating workers to higher skill levels;

(iii) Minimizing the costs relating to cross-training; and,

(iv) Ensuring adequate levels of labor-related flexibility in terms of both *multi-functionality* and *machine coverage* (these are defined below).

Given a set of workers with specified skills, a set of machines, and part demand requirements, the objective of the model is to derive optimal production assignments, as well as machine and operator assignments. This induces optimal levels of cross-training and shift assignments required for the workers. We introduce the following notation at the outset:

Indexes:

$i \in I$	Index of workers
$j \in J$	Index of shift-teams: <A, B1, B2, C1, C2, C3>
$m \in M$	Index of machines
$t \in T$	Index of weeks in the work scheduling cycle: <1,2,3,4,5,6>
$s \in S$	Index of shifts: <1=day; 2=evening; 3=night>
$k \in K$	Index of skill categories: <C, D, E, F, G, H>

Parameters:

S_{ij} = Additional salary costs of employing operator i in shift-team j;

T_{ik} = Additional salary costs of employee i operating in skill category k;

U_{im} = Training costs for operator i on machine m (=0 if the operator is already trained for the machine);

V_m = Demand (= total machine hours required for machine m during work scheduling cycle)

C_{km} = 1 if machine m requires an operator with skill category k;
= 0 if not

SMC_m = Capacity of machine m in a single shift (machine hours)

α_m = Machine-labor efficiency factor. This factor indicates the relation between machine and labor hours. If α_m=1,3 then machine m runs for 1,3 hours while only 1 hour is needed at the machine for a qualified worker. It is assumed that the worker is able to do other machining tasks in the time that is saved through the efficiency factor.

SLC_i = Capacity of worker i in a single shift (labor hours)

RLU_i = Required labor utilization in a single shift (as a fraction of SLC_i)

D_{jts} = 1 if shift-team j operates in shift s in week t; = 0 if not

Decision Variables:

x_{ij} = 1 if worker i is assigned to shift-team j; = 0 if not

y_{ik} = 1 if worker i is employed in skill category k; = 0 if not

z_{im} = 1 if worker i can operate machine m; = 0 if not.

X_{mts} = hours scheduled on machine m in <week t, shift s>

H_{imts} = hours scheduled for operator i, on machine m in <week t, shift s>

W_{imts} = 1 is operator i is needed to operate machine m in <week t, shift s>;
= 0 if not

P_{its} = 1 if worker i is assigned to work in <week t, shift s>; = 0 if not

Q_{mts} = 1 if work is assigned to machine m in <week t, shift s>; = 0 if not

d_{its}^- = underachievement in multi-functionality (MF) goal (of worker i, in week t and shift s)

D_{mts}^- = underachievement in machine coverage (MC) goal (of machine m, in week t and shift s)

Based on the above, the goal program may now be stated as:

Minimize:

$$\Phi_1\ d_{shift}^+ + \Phi_2\, d_{skill}^+ + \Phi_3\, d_{cross\text{-}training}^+ + \Sigma_i\, \Sigma_t\, \Sigma_s\, [\Phi_{4,its}\, d_{MF,its}^-] + \Sigma_m\, \Sigma_t\, \Sigma_s\, [\Phi_{5,mts}\, d_{MC,,mts}^-] \qquad (1)$$

Subject to:

$$\Sigma_t\, \Sigma_s\ X_{mts} = V_m \qquad \forall m \qquad (2)$$

$$X_{mts} \leq SMC_m \qquad \forall m, t, s \qquad (3)$$

$$\Sigma_i\ \alpha_m H_{imts} = X_{mts} \qquad \forall m, t, s \qquad (4)$$

$$\Sigma_m\ H_{imts} \ \leq\ SLC_i \qquad \forall i, t, s \qquad (5)$$
$$\Sigma_m\ H_{imts} \ \geq\ RLU_i * SLC_i \qquad \forall i, t, s \qquad (6)$$
$$\Sigma_m\ H_{imts} \ \leq\ \Omega P_{its} \qquad \forall i, t, s \qquad (7)$$
$$\Sigma_i\ H_{imts} \ \leq\ \Omega Q_{mts} \qquad \forall i, t, s \qquad (8)$$
$$H_{imts} \ \leq\ \Omega\ z_{im} \qquad \forall i, m, t, s \qquad (9)$$
$$z_{im} \leq\ y_{ik}\, C_{km} \qquad \forall i, m, k \qquad (10)$$
$$P_{its} \leq\ x_{ij}\, D_{jts} \qquad \forall i, m, t \qquad (11)$$
$$\Sigma_i\, x_{ij} = 1 \qquad \forall j \qquad (12)$$
$$H_{imts} \ \leq\ \Omega W_{imts} \qquad \forall i, m, t, s \qquad (13)$$
$$\Sigma_i\, \Sigma_j\, S_{ij}\, x_{ij} - d_{shift}^{+} = 0 \qquad (14)$$
$$\Sigma_i\, \Sigma_k\, T_{ik}\, y_{ik} - d_{skill}^{+} = 0 \qquad (15)$$
$$\Sigma_i\, \Sigma_m\, U_{im}\, z_{im} - d_{cross\text{-}training}^{+} = 0 \qquad (16)$$
$$\Sigma_m\, W_{imts} + d_{MF,its}^{-} - d_{MF,its}^{+} = 2P_{its} \qquad \forall i, t, s \qquad (17)$$
$$\Sigma_i\, W_{imts} + d_{MC,mts}^{-} - d_{MC,mts}^{+} = 2Q_{mts} \qquad \forall m, t, s \qquad (18)$$
$$P_{its}, Q_{mts}, W_{imts}, x_{ij}, y_{ik} \text{ and } z_{im} = 0 \text{ or } 1 \qquad \forall i, j, k, m \qquad (19)$$

The objective function includes five conflicting goals to which are assigned weights of Φ_1 through Φ_5. The first of these five goals attempts to minimize the cost of assigning workers to various shift-types. The deviational variable d_{shift}^{+} is linked with the associated x_{ij} decision variables in constraint (14). As stated earlier, typically 2-shift and 3-shift systems involve additional salaries. The second term seeks to minimize the cost relating to placement of workers in various skill levels. The deviational variable d_{skill}^{+} is derived from goal constraint (15) and refers to the y_{ik} decision variables. The skill levels assigned to the workers (y_{ik}) are determined eventually by worker-machine capabilities established (decision variables z_{im}). When workers are required to operate certain machines, their skill categories may be elevated, which may increase their salaries. This is sought to be minimized by the second objective function term.

Likewise, when workers are required to operate certain machines, they may also have to be cross-trained to operate these machines. The third term in the objective function attempts to minimize this cost related to cross-training various workers to operate various machines. The deviational variable $d_{cross\text{-}training}^{+}$ is linked to the required worker-machine capabilities (z_{im}) in goal constraint (16).

The fourth and fifth terms attempt to maximize labor-related flexibility, in terms of the two factors, *multi-functionality (MF)* and *machine coverage (MC)*, as defined in Suresh and Slomp (2001). The functional capabilities in a manufacturing system (cell) may be viewed in terms of labor-machine linkages, as shown in Figure 2.

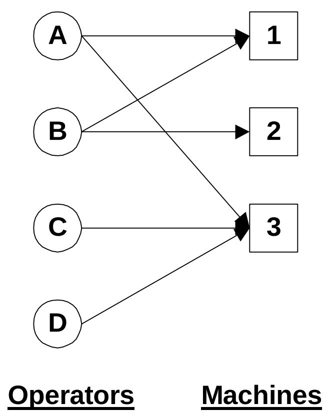

Figure 2. Labor-machine linkages

Multi-functionality of a worker refers to the capability of performing more than one function. This is reflected by the number of linkages emanating from every worker node in the figure. Multi-functionality enables mobility within the department (or cell) and it enables adjustments to demand rates, reduces vulnerability due to absenteeism, machine breakdowns, non-arrival of materials, and other disruptive effects. Multi-functionality also permits temporary assignment of a worker in another department or cell where the workload is high, and where the worker can perform a function within the domain of his/her capabilities.

Machine coverage for a machine pertains to establishing multiple linkages to a machine so that a machine is capable of being operated by more than one worker. This serves to counter absenteeism, temporary non-availability of a worker who is occupied with another task, demand instabilities, etc. This flexibility may be viewed as the number of linkages converging on a machine node in Figure 2.

While augmenting multi-functionality of workers through adequate levels of cross-training, it is desirable to keep in mind the findings from research on dual resource-constrained (DRC) systems (e.g., Treleven 1989; Malhotra *et al*. 1993). This stream of research has indicated consistently that cross-training has a significant effect on reducing manufacturing lead times, work-in-process inventories, and alleviating congestion and improving the flow, but these benefits are subject to diminishing marginal returns. That is, the benefits derived from increasing MF and MC from, say one to two, may be much greater than say, increasing them from a level of two to three. Excessive amounts of cross-training are not required, and even a small amount, directed at key functions goes a long way towards improving the flow.

The two measures, MF and MC, are sought to be enhanced by the fourth and fifth terms in the objective function, respectively. These terms are linked to the goal constraints (17) and (18). These two goals may be in conflict with the first three objective function goals of minimizing other worker-related costs. As will be seen in section 4, multi-functionality and machine coverage can alternatively be controlled by hard constraints.

Constraint (2) ensures that the total load on a machine, V_m, during the planning cycle is split into individual machine loads on each shift (X_{mts}). Constraint (3) ensures that these loads on each machine are within the machine capacity in each shift.

Next, using constraint (4), the machine loads are split into individual operator assignments (H_{imts}) for each shift. Constraint (5) ensures that the total load for each worker, on all the machines assigned in the shift, is within the shift capacity in each shift. Constraint (6) imposes a reasonable level of utilization for each worker assigned to a shift. These worker assignments on various machines in each shift are permitted only if a worker is assigned to work in that shift. This is controlled by setting the P_{its} variables in constraint (7). Constraint (8) sets the Q_{mts} variables, which indicate whether or not machine m will be used in week t and shift s. The variables P_{its} and Q_{mts} show which workers and which machines are active in week t and shift s. This information is needed to establish useful levels of multi-functionality and machine coverage in each week t and shift s (constraints 17 and 18).

The capability of a worker to work on a machine is specified by the 0/1 variable, z_{im}, as stated before. Constraint (9) ensures that production assignments for workers on various machines are in line with the worker-machine capabilities. In constraint (10) these capabilities are linked to the skill categories associated with various machines. The ability to operate a machine implies a skill category, which may affect the skill-related salary premiums, and which are sought to be minimized by the second term in the objective function.

Constraints (11) to (12) specify the restrictions on shift-team assignments. Constraint (11) ensures compatibility between shift-team assignments and machine hours assigned to a worker. Constraint (12) states that each worker should be assigned to only one shift-team. Constraint (13) ensures the availability of worker i to perform on machine m in week t and shift s, if he is needed.

Constraint (14) to (18) are the goal constraints. To elaborate, constraint (14) concerns the total salary consequence due to shift work. This constraint is linked to the first objective term in the objective function. Constraint (15) determines the salary increase due to changes in skill category of the assigned workers and is connected with the second objective in the objective function. Constraint (16) concerns the required training effort and is linked with the third objective in the objective function. Constraints (17) and (18) are goal constrains which, through the fourth and fifth objective function terms, strive to achieve a level of two.

The goal constraints are followed by the integrality and non-negativity specifications. The integer variables in the formulation are the P_{its}, Q_{mts}, W_{imts}, x_{ij}, y_{ik} and z_{im} variables, while the continuous variables include the production assignment variables X_{mts} and H_{imts}. The resulting computational complexity warrants a search for a pragmatic solution procedure. The integration of a production planning problem (i.e. the calculation of the $H_{i,m,t,s}$ and the X_{mts} variables) in the formulation is useful in order to optimize labor allocations and to minimize the need for additional training. This integration, however, is largely responsible for the resulting complexity of the formulation.

In the next section we present an alternative problem formulation where the production planning problem is solved at an aggregate level, in the first phase. The alternative formulation was found to be more computationally amenable and, perhaps more importantly, it provides for an easier incorporation of subjective and problem-specific inputs into the decision process.

4. A Pragmatic Formulation and Solution Procedure (Problem P2)

The alternative procedure consists of two phases, which includes an initial heuristic phase. In this first phase, the operating shifts in which each machine is to be operated are determined from demand requirements. Following this, the sizes of the various shift-teams are also determined heuristically. These decisions form the inputs for the second phase, in which specific assignment of workers to teams are made based on the conflicting objectives presented under problem P1. This second phase also determines the need for additional cross-training required, and skill requirements needed for workers. Thus, the results or outcomes of the first phase become the specifications for the second phase, which is concerned with realizing the required qualifications per shift in a cost-efficient manner. As for problem P1, the second phase employs an integer goal programming model.

Phase I: Choice of Operating Shifts and Shift-Team Composition

Phase 1 can be seen as a medium-term production planning problem. Decisions are taken with respect to the shifts (day, evening, night) in which each machine has to be used and the number of workers that has to be assigned to each shift-team (A, B1, B2, C1, C2, and C3). New decision variables are introduced for the purpose of phase 1:

N_m = No. of shifts in which each machine has to be used
A_{ms} = 1 if machine m has to be used in shift s; = 0 if not
D_j = No. of employees needed in shift-team j

First, we compute the number of shifts (N_m) in which each machine has to be used. This is computed from the demand for the machine during the planning cycle, V_m:

$$N_m = \left\lceil V_m / \ (SMC_m \ * \ 5 \text{ days per week} * T\ ) \right\rceil^{+} \qquad (20)$$

For instance, in Table 2, the annual demand for the automatic turning machine 80127 is 2896 hours. The number of scheduling cycles per year is approximately 48 weeks divided by the cycle length (T = 6 weeks) = 13. The demand in the scheduling period for machine m (V_m) , therefore, is approximately 2896 / 13 = 222.8 hours. Suppose that the effective available machine capacity per shift (SMC_m) is 7 hours. The number of shifts in which machine m has to be used is, according (20), $\lceil 222.8/(7*5*6 \rceil^+ = \lceil 1.06 \rceil^+ = 2$.

Next, the specific shifts (day, evening or night) in which machine m is to be operated need to be determined. These are stated in terms of the zero/one A_{ms} values. Given the N_m values, the values of A_{ms} can be determined directly keeping in mind that, in general, earlier shifts may be preferred due to the lower labor costs associated with day and evening shifts. In the particular case of the automatic turning machine 80127 the A_{ms} will be 1 for the day and evening shift and 0 for the night shift.

This heuristic determination of A_{ms} reduces computational complexity of the second phase significantly, at the expense, however, of providing only a near-optimal solution. At the same time, it must be stressed that mathematical programming formulations, however rigorous, often tend to bypass "practical solutions" which take into account a whole range of subjective, and unarticulated concerns in production planning. A production manager, for instance, may demand that machine 80127 can also be used by qualified workers during the night shift (i.e. $A_{m,night}$=1) because of its dominant position in many routings. Keeping this phase heuristic and interactive also tends to ensure greater transparency, participation, and control of the model on the part of managers. Table 4 presents the A_{ms} values determined for cell II of the case of section 2.

Next, the values of A_{ms} can be used to determine the number of operators required in each shift-team (D_j). The total number of operators has to be divided among the shift-teams (A, B1, B2, C1, C2 and C3) in such a way that there are enough operators in each shift to operate the selected machines. This is computed by using the following simple procedure:

1. The maximal number of workers to be selected for each of the three-shift system teams (C1, C2 and C3) equals the number of machines that have to be used in the night shift. This is given by the number of machines scheduled to be operated during the night shift as indicated by the non-zero A_{ms} values (for s = 3). Depending on the need for capacity on these machines, the production manager may decide to select fewer workers for the three-shift system teams.

2. Next, the maximal number of operators needed for the two-shift system teams (B1 and B2) equals the number of machines that have to be used in the evening shift minus the number of machines that have to be used in the night shift. This is given by the machines for which $A_{m,evening}$- $A_{m,night}$ equals one. Depending on the need for capacity on these machines, the production manager may decide to select fewer workers for the two-shift system teams.

3. The remaining, unassigned workers in the pool are assigned to the day-shift, team A.

As an example, using this stepwise procedure, with Table 4 as input, the production manager has decided for a 1, 2, 2, 2, 2, 2 workers assignment to the shift-system teams A, B1, B2, C1, C2, and C3 of team II. As can be seen in Table 3, there are 11 workers active in cell II.

TABLE 4 Shifts in which machines need to be applicable
(1 = applicable, 0 = not applicable)

Machines\shifts	Morning	Afternoon	Night
80142	1	0	0
81351	1	1	0
80153	1	1	0
80159	1	1	0
80154	1	1	0
81352	1	1	1
80156	1	1	1
80241	1	0	0
80157	1	1	0

Phase II: Team Assignments and Cross-training Requirements

After determining the machines which have to be operated in the various shifts (A_{ms}) and the number of employees needed in each team (D_j), the various operators have to be assigned to the various shift system teams. In addition, the skill requirements needed for each worker are to be determined.

The outcomes of the decision variables in Phase I form parameters for the second phase. The decision variables for phase II are:

w_{ijm} = 1 if worker i performs in team j and can operate machine m; = 0 if not

x_{ij} = 1 if worker i performs in shift-team j; = 0 if not

y_{ik} = 1 if worker i need to be employed in skill category k; = 0 if not

z_{im} = 1 if worker i has to be able to operate machine m; = 0 if not.

In comparison with the general problem formulation of section 3, w_{ijm} is a new variable, which will specify the aggregate planning decisions made in phase I.

The goal programming model for Phase II can be presented as follows:

$$Minimize\ \Phi_1\ d_{shift}^+ + \Phi_2\ d_{skill}^+ + \Phi_3\ d_{cross\text{-}training}^+ \qquad (21)$$

$$\Sigma_m\ w_{ijm} \le \Omega\ x_{ij} \qquad \forall\ i, j \qquad (22)$$

$$\Sigma_j\ \Sigma_m\ C_{km}\, w_{ijm} \le \Omega\, y_{ik} \qquad \forall\ i, k \qquad (23)$$

$$\Sigma_j\ w_{ijm} \le \Omega\, z_{im} \qquad \forall\ i, m \qquad (24)$$

$$\Sigma_i\ x_{ij} = D_j \qquad \forall\ j \qquad (25)$$

$$\Sigma_j\ x_{ij} = 1 \qquad \forall\ i \qquad (26)$$

$$\Sigma_i\ \Sigma_j\ A_{ms}\, D_{jts}\, w_{ijm} \ge MINMC\ A_{ms} \qquad \forall\ m, t, s \qquad (27)$$

$$\Sigma_j\ \Sigma_m\ w_{ijm} \ge MINMF \qquad \forall\ i \qquad (28)$$

$$\Sigma_i\ \Sigma_j\ S_{ij}\, x_{ij} - d_{shift}^+ = 0 \qquad (29)$$

$$\Sigma_i\ \Sigma_k\ T_{ik}\, y_{ik} - d_{skill}^+ = 0 \qquad (30)$$

$$\Sigma_i\ \Sigma_m\ U_{im}\, z_{im} - d_{cross\text{-}training}^+ = 0 \qquad (31)$$

$$w_{ijm}, x_{ij}, y_{ik}\ and\ z_{im} = 0\ or\ 1 \qquad \forall\ i, j, k, and\ m \qquad (32)$$

It may be noted that there are now only three terms in the objective function. This is due to the fact that multi-functionality and machine coverage are now stated in terms of hard constraints (27) and (28) in P2. This has been done to present an alternative approach for the labor flexibility requirement. The three terms in the objective function (21) are explained in section 3.

Constraints (22) through (24) ensure compatible assignments of workers to teams, placement of operators in various skill categories, and the assignment of workers to eligible machines.

Constraint (25) ensures that number of workers assigned to each shift-team equals Dj which is passed on as a parameter from Phase I. Constraint (26) forces each employee to be assigned to only one team.

Constraints (27) and (28) illustrate how multi-functionality and machine coverage constraints can be stated in shift-specific terms and/or in overall terms. For instance, constraint (27) enforces that at least MINMC (= minimal machine coverage) workers are able to operate a machine in each shift in which the machine is scheduled. The availability of two workers serves to counter disruptive problems such as absenteeism. Constraint (28) ensures an adequate overall level of multi-functionality: each worker is capable of working on minimally MINMF (= minimal multi-functionality) machines. This constraint can be made specific to each shift, if needed. Constraints (29) to (31) concern the goal constraints and are explained in section 3. Constraint (32) specifies integrality and non-negativity requirements.

The model of phase 2 can either be seen as *a weighted or a lexicographic* integer goal programming formulation. The weighted integer goal programming formulation minimizes a weighted sum of unwanted deviations from the decision maker's set of targets. All goals are considered simultaneously. The weights in the above formulation are indicated as Φ_1, Φ_2 and Φ_3. In the lexicographic integer goal programming formulation, the symbols Φ_1, Φ_2 and Φ_3 indicate a priority sequence between the various goals. The solution is gained by demanding that the higher priority goals are satisfied as closely as possible and only than that goals are considered with lower priority goals. Many managerial problems have a lexicographic character.

A major advantage of the two-phase heuristic method presented in this section is the fact that the method allows for integrating numerous factors of practical relevance. These include subjective considerations on the part of shop floor managers in operating certain machines in certain shifts, the determination of the number of workers in the various teams to ensure harmonious functioning, initial assignment decisions (X_{ij}) in order to maximize learning opportunities among workers, etc. In the next section, we consider a numerical example to illustrate the functioning of the proposed method (basically phase 2).

5. Numerical Example

The numerical example considered applies to cell II of the case situation, described in section 2. Table 5 presents the additional salaries for operators on account of operating in various shift-teams. It is seen that the two-shift teams (B1 and B2) and three-shift teams (C1, C2, and C3) involve salary premiums.

TABLE 5 Additional monthly salary (in €) if an employee of cell II works in a particular shift team

worker\team	A	B1	B2	C1	C2	C3
19	0	200	200	275	275	275
20	0	175	175	250	250	250
21	0	190	190	260	260	260
22	0	160	160	240	240	240
23	0	175	175	250	250	250
24	0	160	160	240	240	240
25	0	175	175	250	250	250
26	0	145	145	230	230	230
27	0	160	160	240	240	240
28	0	175	175	250	250	250
29	0	145	145	230	230	230

Table 6 presents the salary increase due to elevation of skill categories that apply to the employees in cell II. The employees are not allowed to bypass a skill category. This can be expressed by stating high values in non-applicable cells.

TABLE 6 Salary increase (in €) due to a move to another skill category in cell II

worker\skill category	D	E	F
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	90
25	0	0	100
26	0	0	80
27	0	0	90
28	0	0	100
29	0	0	80

TABLE 7 Training costs per worker per machine in cell II (estimated as €20 per machine training week)

machine worker	80142	81351	80153	80159	80154	81352	80156	80241	80157
19	200	200	1600	1600	1600	1600	1600	200	1600
20	200	200	1600	1600	200	200	200	200	1600
21	200	200	1600	1600	200	200	200	200	1600
22	200	1600	1600	1600	1600	200	200	800	1600
23	200	200	1600	1600	1600	200	200	800	1600
24	1040	200	1600	1600	1600	1600	1600	800	1600
25	200	200	1600	1600	200	1600	1600	800	200
26	200	1600	200	200	200	1600	1600	800	200
27	200	1600	200	200	1600	1600	1600	800	1600
28	200	1600	200	200	1600	1600	1600	800	1600
29	200	200	1600	1600	1600	1600	1600	800	1600

Table 7 shows the cross-training costs assumed. These may be related to the existing worker-machine capabilities shown in Table 2. Training for a particular machine is done on-the-job and not in a continuous mode. It is assumed that each week in the machine training time (see Table 2) corresponds to training costs of € 20. The machine training times mentioned in Table 2 indicate the time needed to become an experienced worker at each of the machines. For this numerical example, it is also assumed that some training costs (€ 200) appear if a worker is assigned to machines for which he/she is already trained. This is in line with the philosophy of a learning organization. In the specific case situation considered, a Total Productive Maintenance Program has been started whereby workers are also trained in maintenance tasks.

Phase 1 of the proposed solution procedure determines the A_{ms} and D_j values, as described in the previous section. The parameter values from Tables 5, 6 and 7 are used for deriving S_{ij}, T_{ik}, and U_{im} values. The values of D_{jts} can be derived from Table 3. The C_{km} values are derived from Table 2.

The integer goal program of problem P2 was executed using the LINGO modeling language (LINDO Systems 1999). The use of this modeling language provides several advantages in an interactive environment. It facilitates rapid generation of mathematical programming formulations. It also facilitates rapid reformulation due to change in parameter values. Another major advantage is that inputs can be read directly from a spreadsheet file, and output routed to different portions of the same spreadsheet file. The LINGO formulation of the problem to be solved here is presented in an Appendix. The formulation has 792 integer variables and 392 constraints.

The problem of phase 2 was solved as a lexicographic integer goal program. The first priority of the production manager is to minimize the elevation of the skill levels of the workers (Φ_2). A too highly skilled workforce is costly and will, in the course of time, lead to worker dissatisfaction. It is assumed that the production manager wants to avoid the situation that skilled workers have to be assigned to less interesting work. The second priority is to minimize the additional costs of allocating workers to the two-day shift and three-day shift system. The third priority concerns the minimization of the total amount of training costs. It makes little sense to train too many workers for operating each of the machines, as DRC systems research has pointed out consistently in the past. Training of workers on various equally complex machines may be important in the longer term as the demand mix changes. It is assumed that the minimum machine coverage (MINMC) in each shift, where the machine has to be used, equals one. This means that the manager accepts the risk that one or more machines cannot be used because of the absenteeism of a worker. The minimum multi-functionality (MINMF) is set to a value of two. If there is not enough work for a particular machine, workers have to be able to move to other machines.

Based on the above priorities, and using the parameter settings, the model of phase 2 was solved in three stages. In the first stage, the additional cost because of changes in skill level is minimized. This minimal cost is added as a constraint the second stage of the model. This stage is concerned with minimization of the cost of assigning workers to shift work. The outcome of this stage creates an additional constraint for stage 3 in which the total training cost is minimized.

TABLE 8 Worker assignment results (Φ_1=0, Φ_2=1, Φ_3=0; MINMF=2 MINMC=1)

	shift team						required machine skill levels			machines								
worker	A	B1	B2	C1	C2	C3	D	E	F	80142	81351	80153	80159	80154	81352	80156	80241	80157
19	0	0	0	0	0	1	0	0	1	0 (-)	0 (-)	0	0	1 (+)	0	1 (+)	0 (-)	1 (+)
20	0	0	1	0	0	0	0	1	0 (*)	0 (-)	0 (-)	1 (+)	1 (+)	0 (-)	0 (-)	0 (-)	0 (-)	1 (+)
21	0	0	0	0	1	0	0	0	1	0 (-)	0 (-)	0	0	0 (-)	0 (-)	1	0 (-)	1 (+)
22	0	1	0	0	0	0	1	1	0 (*)	1	0	0	0	1 (+)	0 (-)	0 (-)	0	1 (+)
23	0	0	0	1	0	0	0	0	1	0 (-)	0 (-)	0	0	0	0 (-)	1	0	1 (+)
24	0	0	0	0	0	1	0	1	0 (*)	0	1	0	0	0	1 (+)	0	0	0
25	0	0	0	1	0	0	0	1	0	0 (-)	1	0	0	0 (-)	1 (+)	0	0	0
26	1	0	0	0	0	0	1	1	0	0 (-)	0	0 (-)	0 (-)	1	0	0	1 (+)	0
27	0	1	0	0	0	0	0	1	0	0 (-)	0	1	1	0	0	0	0	0
28	0	0	0	0	1	0	0	1	0	0 (-)	1 (+)	0 (-)	0 (-)	0	1 (+)	0	0	0
29	0	0	1	0	0	0	1	1	0	1	0 (-)	1 (+)	0	1 (+)	0	0	0	0

d_{shift}^{+}= 2165 , d_{skill}^{+}= 0 , $d_{crosstraining}^{+}$=28200

(*) means that the worker is positioned in a too high salary level. Based upon the required skill levels, a lower salary level would be more appropriate.

(-) means that the worker is not needed to operate the particular machine, although he is qualified;

(+) means that the worker has to be trained for the particular machine

TABLE 9 Worker assignment results (Φ_1=1, Φ_2=0, Φ_3=0, additional constraint d_{skill}^{+}=0 ; MINMF=2 MINMC=1)

	shift team						required machine skill levels			machines								
worker	A	B1	B2	C1	C2	C3	D	E	F	80142	81351	80153	80159	80154	81352	80156	80241	80157
19	1	0	0	0	0	0	1	1	0 (*)	0 (-)	1	0	1 (+)	0	0	0	1	0
20	0	0	0	0	0	1	0	0	1	0 (-)	0 (-)	0	0	0 (-)	0 (-)	1	0 (-)	1 (+)
21	0	0	0	0	1	0	0	0	1	0 (-)	0 (-)	0	0	0 (-)	0 (-)	1	0 (-)	1 (+)
22	0	0	0	1	0	0	0	0	1	0 (-)	0	0	0	0	0 (-)	1	0	1 (+)
23	0	0	0	1	0	0	0	1	0 (*)	0 (-)	1	0	0	0	1	0 (-)	0	0
24	0	0	1	0	0	0	1	1	0 (*)	1(+)	0 (-)	0	1 (+)	0	0	0	0	0
25	0	0	0	0	1	0	0	1	0	0 (-)	1	0	0	0 (-)	1 (+)	0	0	0 (-)
26	0	1	0	0	0	0	1	1	0	1 (-)	0	0 (-)	1	0 (-)	0	0	0	0 (-)
27	0	0	1	0	0	0	0	1	0	0 (-)	0	1	0 (-)	1(+)	0	0	0	0
28	0	0	0	0	0	1	0	1	0	0 (-)	1 (+)	0 (-)	0 (-)	0	1 (+)	0	0	0
29	0	1	0	0	0	0	0	1	0	0 (-)	0 (-)	1 (+)	0	1 (+)	0	0	0	0

d_{shift}^{+}= 2110 , d_{skill}^{+}= 0 , $d_{crosstraining}^{+}$=20840

(*) means that the worker is positioned in a too high salary level. Based upon the required skill levels, a lower salary level would be more appropriate.

(-) means that the worker is not needed to operate the particular machine, although he is qualified;

(+) means that the worker has to be trained for the particular machine

TABLE 10 Worker assignment results (Φ_1=1, Φ_2=0, Φ_3=0, additional constraints $d_{skill}^{+}=0$ and $d_{shift}=2110$; MINMF=2 MINMC=1)

	shift team						required machine skill levels			machines								
worker	A	B1	B2	C1	C2	C3	D	E	F	80142	81351	80153	80159	80154	81352	80156	80241	80157
19	1	0	0	0	0	0	1	0 (*)	0 (*)	1	0 (-)	0	0	0	0	0	1	0
20	0	0	0	1	0	0	0	1	1	0 (-)	0 (-)	0	0	1	1	1	0 (-)	1 (+)
21	0	0	0	0	0	1	0	1	0 (*)	0 (-)	0 (-)	0	0	1	1	0 (-)	0 (-)	0
22	0	0	0	0	1	0	0	1	1	0 (-)	0	0	0	0	1	1	0	1 (+)
23	0	0	0	0	0	1	0	0	1	0 (-)	0 (-)	0	0	0	0 (-)	1	0	1 (+)
24	0	1	0	0	0	0	1	1	0 (*)	0	1	0	0	0	0	0	1 (+)	0
25	0	0	0	0	1	0	0	1	0	0 (-)	1	0	0	1	0	0	0	0 (-)
26	0	1	0	0	0	0	0	1	0	0 (-)	0	1	1	0 (-)	0	0	0	0 (-)
27	0	0	1	0	0	0	0	1	0	0 (-)	0	1	1	0	0	0	0	0
28	0	0	0	1	0	0	0	1	0	0 (-)	0	1	1	0	0	0	0	0
29	0	0	1	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0

$d_{shift}^{+}= 2110$, $d_{skill}^{+}= 0$, $d_{crosstraining}^{+}= 9800$

(*) means that the worker is positioned in a too high salary level. Based upon the required skill levels, a lower salary level would be more appropriate.

(-) means that the worker is not needed to operate the particular machine, although he is qualified;

(+) means that the worker has to be trained for the particular machine

The results of the three stages in solving the lexicographic integer goal programming problem are provided in Tables 8 through 10. As can be seen, the solution has been improved gradually. The final solution shows that workers can be assigned to the various shift teams in such a way that no workers needs to be elevated to a higher skill category and four additional trainings (workers 20, 22 and 23 at machine 80157, and worker 24 at machine 80241) are needed.

It is interesting to observe that worker 22 needs to be trained for the index machine 80157, although worker 25, who is able to operate the machine, is assigned to the same shift team. It is, therefore, possible to save a training expense by assigning worker 25 to machine 80157, instead of worker 22. The negative consequence of the latter assignment, however, is the need to increase the salary level of worker 22, in order to be consistent with the required skills. Within the priority scheme of the goal programming problem, the manager has made clear that a raise in salary (skill) level needs to be avoided if possible. Nineteen cross-trainings are abundant in the final solution of Table 10, taking into account the limitations of MINMC and MINMF. Three workers are not assigned to machines that reflect their salary, or skill level. These abundant cross-trainings and salary levels offer the firm some flexibility in the longer term, when the shift teams have to be rearranged due to structural changes in the demand. It may also indicate a not optimal cross-training situation and the need for decision support tools.

The computer time required to solve the three stages in the lexicographic integer goal program was about 10 seconds for stage 1 and stage 2, and 2 minutes for stage 3 on a laptop computer (Pentium III processor 500 MHz). The required computer time can be further reduced by reducing the size of the problem in a logical way. For instance, based upon the information presented in Table 2, the production manager may pragmatically decide to assign some workers to particular shift teams.

6. Conclusions

This paper has presented a problem that has not been dealt with in past literature, namely the “shift team formation problem (STFP)”. This problem concerns the assignment of workers to teams that work in a 1-, 2-, or 3-daily-shift system. The problem was formulated as an integer goal programming formulation. The paper subsequently presented a pragmatic solution procedure consisting of two phases.

The first phase solves a medium-term planning problem. Basic decisions are taken concerning the machines to be used during the day, evening and night shift, and the number of workers needed in each shift-system. The second phase concerns the assignment of the various workers to the various shift teams. A shift team consists of workers who are present during the same periods in a work scheduling cycle. The assignment has consequences in terms of required additional training of the workers and additional salary costs due to shift work and possible raises of workers in skill levels. The negative consequences are integrated in the assignment problem by means of an integer goal programming formulation. This formulation can be seen as a weighted or a lexicographic integer goal programming formulation.

A case situation encountered in Dutch manufacturing industry served to stress the relevance of the problem. The applicability of the proposed methodology was illustrated by using the information of this particular case situation.

It needs to be stressed that the proposed methodology can be used for various types of multi-shift manufacturing situations. The basic consideration is that in most multi-shift manufacturing situations, shift teams can be distinguished, the working periods of each shift team are known (i.e. D_{jts}), and the demand for each machine can be estimated fairly accurately. This information is needed in phase I to identify the machines needed in each part (working periods) of the day (= A_{ms}) and to decide about the required size of each shift team (D_j). In most practical situations, these decisions can be taken by means of a simple procedure, as shown in section 4. The results of phase 1 form the input for phase 2, as well as the worker-machine matrix and financial data, presented in Table 2. This information is usually available in most manufacturing firms. The integer programming formulation of section 4 forms a useful starting point to solve the problem.

As stated earlier, this methodology can be used for various types of multi-shift manufacturing situations; the problem is also naturally applicable to cell formation problems, which are currently in the phase of including labor-related issues in more detail. Past work in this stream has been mainly focused on grouping parts and machines into cells, without dealing with labor-oriented issues in detail. The methodology presented in this paper also forms an extension of the research stream devoted to dual resource constrained (DRC) systems.

In the past, flexibility in manufacturing situations has been pursued primarily through acquisition of flexible automation and advanced manufacturing technologies (AMT), but it is becoming increasingly evident that ensuring flexibility of labor resources also forms an essential element of manufacturing and supply chain agility.

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APPENDIX: LINGO FORMULATION

```
MODEL:
SETS:!team formation in multi-shift situation (TFMSS);
  I/O19,O20,O21,O22,O23,O24,O26,O27,O28,O29,O30/:;
  J/TA,TB1,TB2,TC1,TC2,TC3/:NUMBER;
  K/QD,QE,QF/:;
  M/1..9/:;
  N/1..6/:;
  O/MORNING,EVENING,NIGHT/:V;
  IXJ(I,J):
  S, !additional salary costs of employing operator I in team J;
  X; !=1 if worker I performs in team J, else 0;
  IXK(I,K):
  T, !additional salary costs if employee I works in skill category K);
  Y; !=1 if worker I works in skill category K, else 0;
  IXM(I,M):
  U, !training costs for employee I on machine M;
  Z; !=1 if worker I has to be able to operate machine M, else 0;
  MXO(M,O):
  A; !=1 if machine M has to operatable in shift O, else 0;
  KXM(K,M):
  CK; !=1 if machine M requires an operator with skill category K, else 0;
  JXNXO(J,N,O):
  B; !=1 if team J is active in shift O in week N;
  IXJXM(I,J,M):
  W; !=1 if worker i performs in team j and is able to operate machine M;
ENDSETS
DATA:
!import the data from excel;
  A,B,CK,S,T,U=@OLE('C:\LINGO4\TEAMFORMATION.XLS');
```

```
      PI1,PI2,PI3,V,NUMBER=@OLE('C:\LINGO4\TEAMFORMATION.X
LS');
   RO=100000;
   !export the solution back to excel;
     @OLE('C:\LINGO4\TEAMFORMATION.XLS')= X,Y,Z,W;
   ENDDATA
   !-----------------------------------------------------
-----------------------;
   MIN = PI1*@SUM(IXJ(II,JJ):S(II,JJ)*X(II,JJ))
     +PI2*@SUM(IxK(II,KK):T(II,KK)*Y(II,KK))
     +PI3*@SUM(IXM(II,MM):U(II,MM)*Z(II,MM));
   !multifunctionality constraint for machines;
   @FOR(M(MM): @FOR(N(NN): @FOR(O(OO)|A(MM,OO)#EQ#1:
   @SUM(I(II):@SUM(J(JJ):B(JJ,NN,OO)*W(II,JJ,MM)))>=2)));
   !labor  flexibility  constraint  on  number  of  machines
that an operator should be able to handle;
   @FOR(I(II):
     @SUM(J(JJ):@SUM(M(MM): W(II,JJ,MM)))>=2);
   !constraint for worker-team relation;
   @FOR(I(II): @FOR(J(JJ):
     @SUM(M(MM):W(II,JJ,MM))<= RO*X(II,JJ)));
   !constraint for worker-qualification relation;
   @FOR(I(II):@FOR(K(KK):
     @SUM(J(JJ):@SUM(M(MM):CK(KK,MM)*W(II,JJ,MM)))<=
RO*Y(II,KK)));
   !constraint for worker-machine relation;
   @FOR(I(II):@FOR(M(MM):
     @SUM(J(JJ):W(II,JJ,MM))<= RO*Z(II,MM)));
   !constraint for worker-team relation;
   @FOR(I(II):
     @SUM(J(JJ):X(II,JJ))=1 );
   @FOR(J(JJ):
     @SUM(I(II):X(II,JJ))=NUMBER(JJ));
   !domain constraints;
   @FOR(I(II):@FOR(J(JJ):@FOR(M(MM):@BIN(W(II,JJ,MM)))));
   @FOR(I(II):@FOR(J(JJ):@BIN(X(II,JJ))));
   @FOR(I(II):@FOR(K(KK):@BIN(Y(II,KK))));
   @FOR(I(II):@FOR(M(MM):@BIN(Z(II,MM))));
   END
```